APPENDIX III

NEUTRON-INDUCED GAMMA RADIATION SOURCES

Neutron sources or beams, encountered in accelerator or power reactor environments, generate additional radiation sources as they penetrate matter. The neutron interactions produce activated material that remains a hazard long after the neutron source is terminated. The neutron-induced interactions include activation, capture, and fission reactions. Each of these mechanisms present a significant radiation hazard.

ACTIVATION SOURCES

The activation of a material as a function of time depends upon the material being activated and the beam activating the material. The activity buildup consists of both production and decay terms and may be written as

$$A = N\sigma\phi[1 - \exp(-\lambda t_{\text{irrad}})]\exp(-\lambda t_{\text{decay}}) \qquad \text{(III.1)}$$

where

A = activity of the sample as a function of time
N = number of atoms in the sample that are activated $N = m\bar{A}/\text{GAW}$
m = mass of the sample (If multiple isotopes are activated, the mass of each constituent must be considered.)
$\bar{A}$ = 6.023×10^{23} atoms/GAW (Avogadro's number)
GAW = gram atomic weight or mass of a mole of material (g)
σ = cross section for the reaction induced by the flux ϕ (barns/atom)
ϕ = fluence rate or flux (neutrons/cm^2-sec)
λ = decay constant of the activated material
t_{irrad} = time the sample was irradiated or exposed to the flux
t_{decay} = decay time or time the sample was removed from the flux

For material that is activated for a long time relative to its half-life, the activity reaches a constant value or saturates. Saturation occurs as the irradiation time becomes much larger than the decay half-life, and the decay time is short relative to the decay half-life. Under these circumstances, the activity approaches A_{sat}, which is the saturation activity

$$A_{sat} = N\sigma\phi \tag{III.2}$$

Determining the saturation activity is an important exercise because it represents a bounding case for dose rate assessments. Design work often utilizes the saturation activity to ensure that the design will bound any operating condition.

Many common activation gamma sources involve the absorption of a neutron with the emission of a gamma ray. Usually this process involves thermal neutrons. Other reactions involve high-energy or fast neutrons and produce high-LET protons via (n, p) reactions. Examples of activation sources are contained in Table III.1. These sources are frequently produced in reactor or accelerator environments.

Table III.1 Activation Gamma Sources

Reaction	Activation Cross Section (barns)	Half-life	Energy (MeV)	Yield Gammas/ Decay
$^{23}Na(n, \gamma)^{24}Na$	0.534	14.96 hr	1.369	1.00
			2.754	1.00
$^{54}Fe(n, p)^{54}Mn$	1.0	314 days	0.835	1.00
$^{55}Mn(n, \gamma)^{56}Mn$	13.3	2.576 hr	0.847	0.99
			1.811	0.29
			2.11	0.15
$^{59}Co(n, \gamma)^{60}Co$	37.2	5.263 years	1.173	1.00
			1.332	1.00
$^{58}Fe(n, \gamma)^{59}Fe$	1.2	45.6 days	1.095	0.56
			1.292	0.44
$^{58}Ni(n, p)^{58}Co$	1.0	71.3 days	0.51	0.30
			0.81	0.99
			0.865	0.014
			1.67	0.006
$^{94}Zr(n, \gamma)^{95}Zr$	0.075	65.5 days	0.724	0.49
			0.756	0.49
			0.765	1.00

Source: O. J. Wallace, WAPD-TM-1453.

During activation, the absorbed neutron produces a radioactive nuclide that decays with a characteristic half-life. This may be contrasted with capture reactions which involve nearly an instantaneous gamma-ray emission following the capture.

CAPTURE GAMMA SOURCES

Capture gamma sources involve the absorption of a neutron with the nearly instantaneous emission of a gamma ray. Capture reactions are often defined in terms of bulk materials and play an important role in design calculations. Calculations of nuclear radiation heat generation and primary or biological shield design must properly account for capture sources. Examples of capture gamma sources are provided in Table III.2.

FISSION GAMMA SOURCES

Fission gamma sources are produced by the neutron spectrum of a reactor. Table III.3 summarizes the characteristics of two common fission gamma

Table III.2 Capture Gamma Sources

Reaction	Absorption Cross Section (barns)	Density (g/cm^3)	Energy (MeV)	Yield Gammas/ Capture
Hydrogen capture	0.33	8.988×10^{-4}	2.2	1.0
Iron capture	2.53	7.874	1.0	1.85
			7.0	0.86
Zirconium capture	0.180	6.53	1.0	0.7
			5.0	1.42
Uranium capture	7.68	18.95	0.7	3.63
			2.5	1.2
Water capture	0.66	0.998	2.2	1.0
Hafnium capture	105.0	13.29	1.0	0.75
			3.0	2.366
Stainless steel capture	0.0332	7.9	1.0	1.69
			7.0	0.93
Inconel capture	0.0462	8.51	0.5	2.0
			5.5	1.51

Source: O. J. Wallace, WAPD-TM-1453.

Table III.3 Fission Gamma Sources

Source	Energy (MeV)	Yield Gammas/ Fission
^{16}N gammas	2.74	0.01
	6.13	0.69
	7.12	0.05
Prompt and delayed fission gammas	0.80	7.22
	2.0	2.26
	4.0	1.02

Source: O. J. Wallace, WAPD-TM-1453.

sources. The N-16 source is derived from the O-16 (n, p) reaction with the subsequent decay of the short-lived N-16 system. The prompt and delayed fission gamma source represents a collective summary of the uranium fission gamma spectrum. These sources tend to have more varied energies and yields when compared with either the activation or capture sources for specific isotopes.